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SOME ASPECTS OF ASTRONAUTICS

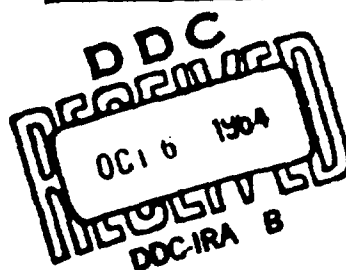
R. W. Bushheim, S. Kerrick,
E. H. Vestins, and A. G. Wilson
Edited by P. Sverling

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SOME ASPECTS OF ASTRONAUTICS

R. W. Buchheim, S. Herrick,
E. H. Vestine, and A. G. Wilson
Edited by P. Swerling*

INTRODUCTION

Those who first venture into space will, unlike earlier navigators pushing across unexplored seas, find that much of the region to be traversed has already been charted and something of the character of both space itself and potential destinations in space is known. But there is always the difference between indirect knowledge and first-hand experience, and this difference undoubtedly will show up trenchantly on the first flights into space.

Before entering into details, a few important basic differences between space environment and terrestrial environment should be mentioned and kept in mind in our discussions of space. First, the configurations of bodies in space are never static; relative distances are always changing. Second, the description of the solar system in terms of distances alone is inadequate. The astronaut must think also in terms of all the orbital elements: the eccentricities, the inclinations, the nodes, the epochs, and the perihelions as well as the semimajor axes. The third general difference is the relation between energy expended and distance traversed. In space this will be completely unlike anything in terrestrial experience. Fourth is the matter of the scale of space. It is always most difficult to visualize the tremendous distances involved. A fifth difference is that space travel will be performed in vehicles which are intermediate in size between the small particles in free space and the massive planets.

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While the motions of the latter are influenced only by gravitational forces (Newtonian and relativistic), the small particles are, in addition, subject to magnetic, electrical, and radiation forces. It is to be expected that future space ships will, as intermediate-sized bodies, experience to some extent the effects of all of these forces.

There are many possible ways to classify space-flight activities, such as powered and ballistic, manned and unmanned, scientific and military, etc. One of the most useful of these ways is to order space flights by flight mission.

The main categories of activities of general interest are:

- o Earth satellites
- o Lunar flights
- o Interplanetary flights

Let us first consider the gross dimensions of these flight classes.

In the case of satellites the distance parameter of interest is orbit altitude. This can range from about 100 miles to about 1,000,000 miles. Beyond about 1,000,000 miles from the earth, the sun's field will disturb the vehicle to such an extent that the term 'earth satellite' tends to lose its meaning. The time parameter of interest is orbit period; this will range from about 1-1/2 hours to about 8 months.

Lunar flight distances are, of course, roughly the distances from earth to moon - about 240,000 miles. Flight times will range generally from about one day to one month or more.

The interplanetary theater starts at a distance from the earth of about 1,000,000 miles and extends to the orbit of Pluto, nearly 5,000,000,000 miles at maximum displacement. Flight times would fall roughly in the range of one month to 50 years.

In the category of satellites we have two principal types:

- o Non-recoverable satellites
- o Recoverable satellites

The non-recoverable earth satellite is now a familiar system. Its feasibility has been established beyond any reasonable doubt.

The recoverable satellite is so contrived that all or part of the satellite is perturbed by an on-board rocket so that it returns to the surface of the earth.

The lunar flight category can be broken down into the following principal missions:

- o Impacts on the moon
- o Non-destructive landings on the moon
- o Artificial satellites of the moon
- o Circumlunar flights

Interplanetary flight would, in turn, involve execution of the following:

- o Impact on the planetary surface. (Impact here has its usual meaning - a destructive collision.)
- o Land intact on the planetary surface.
- o Set up an artificial satellite of the planet.
- o Orbit around the planet and return to earth.
- o Set up interplanetary space buoys.

BASIC LAWS OF CELESTIAL MECHANICS

Celestial mechanics, which is the basis for the determination of orbits or trajectories in space, is usually thought of as beginning with

the publication of the De Revolutionibus by Copernicus in 1543, although the subject has important roots nearly two thousand years before this date.

A second major step was made by Kepler in his discovery of the laws of planetary motion (see Fig. 1):

1. The orbits of the planets are ellipses with the sun at one focus.
2. The line joining the planet to the sun sweeps over equal areas in equal intervals of time.
3. The square of the period (P) of a planet is proportional to the cube of its mean distance (a).

In Kepler's third law the period, usually designated by P , is the length of time it takes the planet, comet, or, today, satellite to travel around its orbit. The mean distance, a , is sometimes called the semimajor axis (cf. Fig. 1) and is in fact the average of the greatest and least distances, the perihelion and the aphelion distances in heliocentric orbits, or the perigee and apogee distances in geocentric orbits.

With his law of universal gravitation and his laws of motion, Newton was able to rederive the Keplerian laws of planetary motion. In doing so he found it necessary to modify them in significant ways:

1. Kepler's laws define the motion of a planet exactly only if it is alone with its sun in the universe. Every other object in the universe will disturb the simple Keplerian motion, producing what we call perturbations. In Fig. 2 we see the effect of an extremely large perturbation. A comet or minor planet is traveling around the sun in Keplerian orbit A. One time, when it is crossing the orbit of Jupiter, it finds Jupiter nearby, at J. Jupiter's attraction is momentarily very large, causing the disturbed object to be hurled off toward the sun in a new direction. After it is

safely past Jupiter the sun's attraction again becomes predominant, and the object thereafter travels in orbit B. Of course the attraction of Jupiter is never negligible, and so is progressively changing the orbit, though more gradually than in the illustration.

2. Newton showed also that Kepler's laws would be exact for a two-body system only if the two bodies were homogeneous in spherical concentric layers. Because of its rotation, the earth is not perfectly spherical, but bulges out at the equator. The bulge will introduce perturbative forces on the moon or an artificial satellite. These cannot be resolved into a single force acting from the center of the earth. The bulge perturbations of the orbit of an artificial satellite are much larger than those caused by the sun or the moon.

Other forces that may be treated as perturbations, when they are not too large, include thrust, drag, and other aerodynamic forces, and possibly electromagnetic forces, radiation pressure, and the modifications introduced into the gravitational field by Einstein mechanics.

3. Kepler's laws, in Newton's redevelopment, emerge as integrals of the two-body problem. There are many other useful integrals, of course, and at least one of them has such a simple form as to be especially useful in the solution or interpretation of orbit problems. It is the vis-viva, or energy integral, which expresses the fact that the sum of the kinetic and potential energies is constant:

$$v^2 = k^2 (m_1 + m_2) \left(\frac{2}{r} - \frac{1}{a} \right)$$

In this equation k is the gravitational constant; m_1 and m_2 are the masses of the two bodies; a is the semimajor axis; v is the velocity; and r is the distance from the focus.

4. Newton found that in the two-body problem the ellipse was not the only possible orbit. Parabolas and hyperbolas were also possible orbits. The addition of parabolas made it possible for Newton to show that the comets, which travel in nearly parabolic orbits, obey the same laws as the planets.

For illustration, let us suppose that a circle is the orbit of a satellite somewhat above the surface of the earth, with a velocity just under 7 miles per second. If the velocity were cut to 3 miles per second, the satellite would fall inward on a smaller ellipse until it encountered the surface of the earth. Conversely if we increased the velocity of our projectile to 8 miles per second, we would find that it would rise up on a larger ellipse. If next we think of the velocity as increased to 7 miles per second along the same horizontal tangent we find that the object will travel off on a parabola, never slowing down enough to return. This critical velocity, approximately 7 miles per second, is called the 'velocity of escape.' It is the same whether the direction of projection is horizontal, vertical, or some angle in between. A velocity of 8 miles per second would carry the projectile off on a hyperbola; still higher velocities, on more nearly rectilinear hyperbolas.

The so-called velocity of escape applies strictly only if we neglect all other forces in the field. With a velocity of 7 miles per second a projectile would escape, at least temporarily, from the earth, but not from the sun. As it receded from the earth, in any direction, its velocity would quickly drop off nearly to zero. But with its geocentric velocity nearly zero, its heliocentric velocity would be nearly the same as that of the earth, i.e., $18\frac{1}{2}$ miles per second in a direction approximately at right

angles to the direction of the sun. And so the escaped vehicle would take up a nearly circular orbit around the sun closely approximating that of the earth.

THE ORBITAL ELEMENTS

A two-body orbit, as illustrated in Fig. 3, is specified by six constants, called the 'elements' of the orbit. Three of these elements have to do with the orientation of the orbit in space, and require that we specify arbitrarily a reference plane, and in that plane a reference direction. For geocentric orbits we use the plane of the earth's equator and the direction of the vernal equinox. (For heliocentric orbits the reference plane is usually the ecliptic plane, i.e., the plane of the earth's orbit.) The intersection of the orbit plane and the equator plane, in the geocentric case, is called the line of nodes. The ascending node is the point at which the object passes from the south side to the north side of the equator, and the descending node is the point at which it passes from north to south. Three angles that may be used for orientation elements are, then:

Ω , the longitude of the node, or the angle between the directions of the vernal equinox and the ascending node.

i , the inclination, or the angle between the two planes.

ω , the argument of perigee, or the angle in the orbit plane between the direction of the ascending node and the direction of perigee.

The remaining elements specify the size and shape of the orbit and the time at which the orbit is at some specified point. These may be:

a , the mean distance or semimajor axis.

e , the eccentricity, which may be defined as the distance from the center of the ellipse divided by the semimajor axis.

T, the time of perigee passage.

These six constants are often replaced by others in part or altogether. For example, the orientation unit vectors, \underline{P} , directed to perigee, \underline{Q} , parallel to the velocity vector at perigee, and \underline{W} , perpendicular to the orbit plane and making up a right-handed system with \underline{P} and \underline{Q} , are often used as orientation elements in place of Ω, i, ω .

PERTURBATIONS AND PRECISION

Two-body orbits and elements are very useful if the perturbing forces are not prohibitively large. Often the perturbing forces may be reduced greatly by relatively simple devices. For example, the attraction of the sun on the moon is approximately twice that of the earth. If the earth and the moon were stationary, the sun would quickly pull the moon away from us. But most of the sun's attraction is used up in pulling the moon into approximately the same curvilinear orbit as that of the earth. What is left over is only about 1/100 of the earth's attraction. Consequently, as the first approximation, the moon's orbit around the earth is approximately a Keplerian ellipse. A perturbation as large as 1/100th of the primary acceleration, however, is extremely large, and the accurate determination of the moon's orbit is a very complicated matter.

Two well-known perturbations of satellite orbits due to an equatorial bulge of the central body are (1) regression of the nodes and (2) advance of the perigee. That is, the nodes gradually move in a direction opposite to that of the orbital motion, while the perigee gradually moves in the same direction as the orbital motion. Perturbations due to drag cause a gradual decrease in the eccentricity and semimajor axis of an orbit. In many cases, the magnitude of these 'secular' perturbations can be calculated

to a good degree of approximation.

There are several different methods for handling perturbations. In one of them we make no reference whatsoever to auxiliary ellipses, but simply integrate the total acceleration, in order to follow the path. This process, used with numerical integration, is called Cowell's method. It has been used in lunar trajectory work almost exclusively. A second way to handle perturbations is to calculate from the position and velocity at any point in the actual path the elliptic orbit that would be followed if at that point all perturbations were suddenly to cease. The differences between the actual accelerations and the 'two-body accelerations' in this 'osculating' ellipse are then integrated to find a correction to a position in the two-body orbit that will give the position in the actual orbit. When numerical integration is used this method is referred to as Encke's method. It is especially effective when the perturbations are small. After a time, however, the perturbations are likely to build up to such a point that a new osculating reference orbit must be determined from integrated position and velocity.

Instead of making abrupt changes from one reference orbit to another, we can make the changes gradually by the method of variation of parameters. In this method the parameters that define the osculating two-body orbit are allowed to vary progressively so that the osculating orbit will always give the same position and velocity as the two-body orbit. The effect will be to cause one of the osculating ellipses gradually to change until it merges into the other one. The variations of the parameters are determined directly from the perturbations and may be integrated numerically, or, alternatively, by series expansions.

When the perturbations are very large, neither Encke's method nor the method of variation of parameters offers any advantage over Cowell's method, and the last should be used because it requires less calculation. When the perturbations are small, however, and especially when the two-body motion is very rapid, Cowell's method is disadvantageous and may even be incapable of handling the problem.

When perturbations are handled by numerical integration the process is called special perturbations. When the perturbations are represented by series and integrated term by term, the process is referred to as general perturbations. Today we refer to such series as 'Fourier series.' Actually the process antedates Fourier by more than two thousand years. In the Ptolemaic system the complex motions of the planets were represented by systems of circles that were equivalent to Fourier series.

It is desirable, at this point, to distinguish clearly between two kinds of trajectory work: 'preliminary (or feasibility) trajectories' and 'precision trajectories.' By preliminary trajectories we mean qualitative trajectories that are useful in preliminary studies, in which only rough estimates of the amount of fuel, the duration of flight, required guidance tolerances, or similar questions are desired. Precision trajectories, on the other hand, are necessary for accurate space navigation.

The lunar flight trajectory illustrates one of the important distinctions between preliminary and precision work. In preliminary studies of lunar and circumlunar trajectories it is possible to suppose that the moon is moving with uniform velocity in a perfect circle, or that it is a fixed point in a rotating framework. In precision work, however, the rotating framework ceases to be useful. In fact there are no simple mathematical

expressions that will represent the moon's position for more than a very brief interval. We must turn to tables of the moon's position, such as those given in the various national ephemerides or almanacs.

Another important consideration in precision orbit work is the following:

At the present time refined values of the basic constants are definitely required before an interplanetary ballistic flight to intersect another planet could be successful. This may seem odd, since centuries of astronomical observations have contributed to plotting the elements of the orbits of planets and satellites to six-place accuracy or better, and to determining the mutual perturbations of these orbits caused by the several bodies in the solar system. However, one dominant factor makes these elements unsuitable for successful planet-to-planet navigation. This factor is that while planetary orbital dimensions are known to six-place accuracy or better when expressed in terms of the astronomical unit (the semimajor axis of the earth's orbit), the astronomical unit (a.u.) itself is known to only about one part in 1500 when expressed in terms of meters or feet, the units in which flight design must be made. (Specifically, $1.495 \times 10^8 \text{ km} \leq 1 \text{ a.u.} \leq 1.496 \times 10^8 \text{ km}.$)

As a simple example of the effect of this uncertainty in the scale of the solar system on a problem in space navigation, consider the trip from the Earth to Venus along a minimum-energy orbit. Making several simplifying assumptions regarding the eccentricities and inclinations of the orbits of the Earth and Venus, we find that the uncertainty in the semimajor axis of the minimum-energy orbit would be about 172,000 km or 15 diameters of Venus; and this neglects the timing error introduced. One of the first tasks of a

flight into interplanetary space should be the measurement of the fundamental astronomical unit of distance in terms of laboratory standards of length. Another basic constant, the gravitational constant, is known to only about three significant figures when expressed in the c.g.s. system or any other laboratory system of units.

LUNAR AND INTERPLANETARY FLIGHTS

A typical preliminary earth-moon transit trajectory computed by automatic machine is shown in Fig. 4. It is plotted in rotating coordinates so arranged that the earth-moon line appears to stay fixed. This coordinate scheme shows the trajectory about as it would appear to an observer standing on the moon. This same trajectory is plotted in inertial coordinates in Fig. 5.

It can be seen in Fig. 5 that the vehicle in this particular transit trajectory will move in a counterclockwise direction in the initial phases of flight; i.e., the advance of vehicle angular position will be in the same direction as the orbital motion of earth and moon. Such an orbit is referred to as a direct orbit. An advantage of such an orbit is the fact that one can capitalize on the orbital motion of the earth (in earth-moon space) as well as the rotation of the earth in building up the initial velocity of the vehicle.

In Fig. 5 the attraction of the moon can be seen near the terminal end of the trajectory. The direction of approach has become almost a straight line to the moon's center.

The time required for an earth-moon passage is strongly dependent upon initial velocity. A plot of transit time as a function of initial velocity is shown in Fig. 6. The exact time-vs-velocity curve is, of course, somewhat

dependent also upon the direction of projection, but the dependence is relatively slight.

This marked decrease in flight time for a moderate velocity increase in the low-speed regime suggests that the efficiency of some flight missions can be enhanced by sacrificing some payload to increase projection velocity. This would be true, for example, in missions requiring the expenditure of large amounts of electrical energy during transit, or in manned flight where the demands of nutrition and a livable environment grow with flight duration.

A lunar-impact flight consists simply of projection of a vehicle from the earth to crash on the surface of the moon unchecked. Such a flight would typically involve traversal of a trajectory like that in Figs. 4 and 5. The speed of the body at impact, relative to the moon's surface, will be no less than lunar escape velocity, and typically would be around 10,000 ft/sec. It is conceivable that some sort of instrument package could be made to survive such an impact, but the possibilities are only of a speculative sort.

A particularly interesting payload possibility for an impact flight is a source of visible light to signal arrival. It has been estimated that something like 10 pounds of flash powder exploded on the dark half of the half-illuminated moon would be observable in a 21-inch reflecting telescope.

The accuracy required in the projection process to produce an impact on the visible side of the moon must be determined by trial and error, i.e., simply by computing a great number of trajectories, noting locations of impacts and miss distances. The values of allowable errors in speed and direction of projection are dependent upon the speed, direction, and position at the initial point in the unpowered trajectory. A coordinate arrangement for defining projection conditions is shown in Fig. 7.

Combinations of initial conditions that result in hits passing through the moon's center are shown in Fig. 8. For nominal values

$$V_0 = 35,000 \text{ ft/sec}$$

$$\gamma = 14.2 \text{ deg}$$

$$\phi = 108 \text{ deg}$$

$$r = 4500 \text{ stat mi}$$

marked in Fig. 8, we find that allowable errors in speed or direction for impact on the visible face of the moon are about

$$\delta V = \pm 40 \text{ ft/sec}$$

$$\delta \gamma = \pm 0.25 \text{ deg}$$

The exact band of conditions for impact, around the nominal point selected, is shown in Fig. 9. Generally speaking, higher values of V_0 lead to larger allowable δV , while smaller values V_0 allow greater values of $\delta \gamma$. Effects of velocity errors are illustrated in Fig. 10.

We must also recognize the existence of another kind of flight tolerance that does not figure in purely terrestrial flight activities - that of launch time. In addition to a fairly close tolerance on the instant of launch, it must be recognized that the calendar dates on which launching is feasible are dependent upon the latitude of the launch site, the range of firing azimuth available, and the inclination of the moon's orbit relative to the earth's equatorial plane. These general observations about launch-time tolerance apply more or less directly to all of the lunar flight types listed.

For most equipments, a non-destructive landing on a solid surface implies an approach to the surface at a rather low speed - a good deal less than 10,000 ft/sec. Since the moon has no appreciable atmosphere, deceleration

must be accomplished by rocket propulsion in the final phase of approach.

The trajectory requirements for lunar landing are essentially the same as those for impact, except perhaps for some closer specification of accuracy tolerances if a nearly perpendicular hit on the lunar surface is needed to accommodate the particular landing-gear arrangement employed. Landing does, however, involve another extension of the problem beyond the impact case. It introduces a requirement for control of the orientation of the vehicle so that the decelerating-rocket thrust is properly aligned relative to the lunar approach velocity.

Another flight mission that requires rocket deceleration at the moon, and, hence, attitude stabilization, is that of establishing an artificial satellite of the moon. For this operation we must proceed along a transit trajectory that misses the moon, to pass by it at an altitude equal to the desired satellite altitude.

The period and orbital velocity of a lunar satellite as a function of orbit altitude is shown in Fig. 11. It is seen that for reasonably close satellites, orbital velocity falls in the vicinity of 5000 ft/sec. Since the velocity of the vehicle in its transit trajectory will be of the order of 10,000 ft/sec near the moon, it is apparent that a velocity reduction of around 5000 ft/sec is required to set up a lunar satellite.

The projection accuracy required in this operation does not differ markedly from that required to lunar impact. The limiting accuracy requirements are derived from consideration of two possible catastrophes that can occur to the satellite: too low an initial velocity will cause it to collide with the moon (Fig. 12); too high a velocity will result in recapture by the earth (Fig. 13).

If we wish to make an unpowered flight entirely around the moon and return to the earth, we must stay near the extreme low end of the scale of lunar flight speeds. In fact, we must operate in the region between about 34,800 and 35,100 ft/sec only (referred to an initial position 4300 miles from the center of the earth). Substantially higher initial velocities would result in speeds near the moon that are too high to permit sufficient deflection of the trajectory by the moon.

Within the allowable range of initial velocities, the accuracy requirements for circumlunar flight are comparatively modest if all we ask is return to the earth: typically ± 75 ft/sec in velocity or ± 5 deg in direction. These large tolerances are, however, associated with fairly large variations in the distance of closest approach to the moon and in total flight time. A variation of 10 ft/sec in initial velocity would change the distance of closest approach by about 1000 miles and the total flight time by about 25 hours. Because of this sensitivity of flight time to initial velocity, the velocity would have to be controlled to within about ± 0.5 ft/sec if a returning circumlunar vehicle were to be recovered within the continental United States. These values of sensitivity apply to a trajectory with an initial velocity of about 34,900 ft/sec which passes the moon at a nearest approach distance of about 4000 mi. The sensitivities for other trajectories could differ from these by as much as an order of magnitude depending upon the exact values of the initial conditions.

There are five special points in earth-moon space, called 'libration centers,' at which a vehicle might 'float at anchor' as a sort of space buoy. The arrangement of these points in the (x,y) plane is shown in Fig. 14. Approximate solutions to the equations of motion can be developed in the neighborhoods of these centers of libration.

We find from this solution that the motion near the straight-line centers of libration (I, II, and III) is unstable; because of the presence of the hyperbolic functions, a particle initially near a center of libration will eventually move indefinitely far away.

For the equilateral-triangle points only oscillatory terms appear in the solution to the equations of motion, so it would seem that we could establish space buoys at the triangle points that would stay at anchor in earth-moon space for an indefinite period, until displaced by external disturbances.

In treating lunar flight we have been concerned with a space environment dominated by the fields of two massive bodies - the earth and the moon - revolving in circles about their common center of mass. When we consider interplanetary flight, the main features of the problem are determined by a similar kind of flight environment. The difference is that the interplanetary flight has more major phases.

Let us run through these phases in a flight, say, from earth to Mars. The first phase takes place in earth-moon space. This phase soon blends into the second phase, where the main sources of influence are the earth and sun. At a distance of a few million miles from the earth, the third phase begins, in which the sole influence of substantial consequence is due to the sun. As we approach Mars we enter the fourth flight phase, where the bodies of chief concern are Mars and the sun. In the terminal, or fifth, phase very near Mars, only the field of Mars itself is important.

The computation of an interplanetary flight trajectory is very complex, because of the multiplicity of flight phases with the attendant requirements for changing reference frames, equations of motion, accuracy scales, etc. However, the major characteristics of an interplanetary trajectory can be

summarized as follows: The initial leg of the trajectory (phase one) approximates a hyperbola with focus at the earth's center; this leg (through phase two) blends into a large ellipse with focus at the sun's center (phase three); near the end (through phase four) this ellipse blends into a hyperbola with focus at the center of the target planet (phase five).

Landing on Mercury would be similar to landing on the moon; there is no atmosphere, so deceleration must be accomplished by rocket. Landings on Venus, Mars, or the earth can make use of aerodynamic drag for deceleration. Landings in the usual sense are not likely on the other planets, since they do not have (or probably do not have) clearly defined solid surfaces.

Establishment of an artificial satellite of another planet involves the same possible sources of failure as establishment of a lunar satellite - too little velocity will result in collision with the planet, too much will lead to capture by the sun. A round-trip around, say, Mars with subsequent return to the earth is possible by proper trajectory arrangements.

Libration centers in interplanetary space are produced by the fields of the sun and a planet, just as they are produced in earth-moon space by the fields of the earth and moon. Thus we should also be able to establish interplanetary space buoys. In fact such buoys already exist in natural form as the Trojan asteroids (see below) at the equilateral-triangle points relative to the sun and Jupiter.

For all of these interplanetary missions the guidance accuracy requirements are far more stringent than for analogous lunar missions. Representative velocity tolerances are on the order of 0.1 ft/sec.

Another type of interplanetary mission is that of establishing an artificial asteroid (artificial solar satellite).

THE SPACE ENVIRONMENT

One of the most important aspects of the space environment deals with the material content of space. Let us first consider bodies in the range from cosmic dust to chunks of rock (i.e., say 20 microns to a few meters) commonly called meteoroids. Figure 15, based upon the observational and theoretical results of the Harvard Meteor Program, gives the mass and size of meteoric particles as functions of the visual magnitude. Figure 16 indicates the number of such meteoroids striking the earth per day, and the number striking a 3-meter sphere in the neighborhood of the earth per day.

It is estimated by Whipple that a meteoroid of magnitude 17, moving with a velocity of 18 km/sec, of which about two per day will strike a 3-meter sphere, will penetrate an aluminum skin of 0.01 cm, whereas a meteoroid of magnitude 5, one of which will strike the sphere every hundred years, would penetrate 4.5 cm of aluminum. About every 50 days a particle capable of penetrating 0.5 cm of aluminum would hit the sphere.

But the probability of striking meteoroids depends upon where the vehicle is in space. Figure 16 applies to the immediate neighborhood of the earth. At greater distances good data are lacking. What is known, however, is that (a) the smallest dust particles (micrometeoroids) are concentrated in the ecliptic or plane of the earth's orbit, and (b) most meteoritic material is cometary refuse and is consequently largely distributed along the orbits of comets.

Let us review some of the evidence for the ecliptic concentration of cosmic dust. After evening twilight, especially near the 21st of March in northern latitudes, a faint tapered band of light can be seen extending up from the horizon centered along the ecliptic. This band of light, which

can be photoelectrically traced through the complete night sky, is called the zodiacal light. The color of the zodiacal light is nearly the same as that of the sun, but shows approximately 21 per cent polarization. These observational facts suggest that the zodiacal light is caused for the most part by sunlight scattered from small dust or meteoroidal particles at least 20 microns in diameter. Since light scattered by free electrons is strongly polarized, it is probable that free electrons represent a fraction of the particles present. This is also substantiated by the fact that the total light present seems to vary with solar activity, being least when ionizing radiations from the sun are at a minimum. However, since scattering by gas atoms and molecules alters the color of the light it must be concluded that the zodiacal particles (except for the free electrons) are much larger than molecules.

It has been suggested that the zodiacal light is an extension of the outer solar corona. This idea is reinforced by the fact that the corona has a color and continuous spectrum agreeing with the zodiacal light. But most interesting is the comparison of the brightnesses, as shown in Fig. 17.

This layer of small meteoroidal particles must extend from the sun well beyond the orbit of the earth, being concentrated toward the ecliptic or fundamental plane of the solar system.

The major concentration of the smallest meteoric material (producing no visual effects when striking the earth) is in the ecliptic, but other concentrations are intimately associated with comets and other bodies. The visible meteors, or shooting stars, are of two types - those associated with showers and those which are sporadic. The shower meteors are of cometary origin; the sporadics are probably traceable to asteroids.

Let us review a few facts concerning comets and meteor showers. No accurate masses of comets have been determined, since they are not massive enough to exert any measurable perturbative forces on other bodies. But it is estimated that typical masses are of the order of 10^{12} tons (earth = approximately 10^{21} tons), and the densities are such that in a thousand cubic miles of a comet's tail there is less matter than in a cubic inch of air.

In 1949 Whipple hypothesized a comet model which satisfactorily explains a great many observed facts about comets. Whipple holds that a comet's nucleus is a cosmic iceberg, a porous mass of solidified gases or ice plus some solid particles. The substances present are largely water ice, ammonia, and methane with some carbon dioxide and cyanogen.

But what is of special interest is that on each trip near the sun, the comet is partially disintegrated and leaves a 'wake' of small solid particles and ices. So the regions of space where an astronaut is likely to find higher than average densities of meteoric material are along the orbit of comets, either 'live' comets or old disintegrated comets.

Whenever the earth passes through one of these cometary wakes a meteor shower results. Hundreds of shooting stars are observed to emerge from a small area of the sky called the radiant, the direction being determined by the orbit of the comet wake in space. In general these small, solid particles or bits of ice, a few microns in size, which cause meteor showers will not cause penetrative disasters to a space vehicle, though they may in time cause considerable skin attrition. It is the sporadic meteoroids that are likely to cause sudden trouble in space flight. These bodies are most probably fragments of asteroids which have resulted from collisions. Like

comets, none seems to have a definitively hyperbolic orbit. However, these sporadic meteoroids may be quite sizable, form fireballs, and frequently strike the earth. They range from a few grams up to thousands of tons like the large meteorites (or even small asteroids) which caused craters like the Barringer Meteor Crater in Arizona.

Let us now turn briefly to some facts concerning the minor planets or asteroids themselves. Since the discovery of the first asteroid on January 1, 1801, the orbits of more than 1500 of these bodies have been determined. However, their total number must run into the hundreds of thousands; it has been estimated that there are 80,000 brighter than the 19th magnitude alone. Most of the asteroids follow orbits which lie between the orbits of Mars and Jupiter, occupying a place in the solar system where Bode's Law has predicted a major planet which does not exist. (Some asteroids depart considerably from the mean orbits.) One family of asteroids is of special interest. It occupies the equilateral libration points in Jupiter's orbit (Fig. 18). These asteroids - known as the Trojans - number about 12, some leading Jupiter, some following. Searches have been made for possible Trojan-type asteroids associated with the equilateral libration points in the orbits of other planets, but none has been found.

Orbits whose periods are exact fractions of Jupiter's period are called resonant orbits. The effect of perturbations on these resonant orbits is to render them unstable and force the asteroids into other orbits, a fact which might be of interest to astronauts; similar effects would operate on earth satellites whose periods were exact fractions of the lunar period. Thus if a satellite were placed on an orbit with a period of say exactly $1/4$ a month, it would soon move into some other orbit.

In recent years high-powered, wide-field photographic telescopes have recorded thousands of faint new asteroids, some of them on orbits which bring them close to the earth; in 1937 an asteroid swept within 800,000 km of the earth, or roughly twice the moon's distance. Orbits are now known for at least ten such objects which come within the earth's orbit. Undoubtedly there are scores more, and over a period of hundreds of thousands of years collisions with the earth must occur.

The largest asteroid (and the first discovered) is Ceres with a diameter of 730 km. The sizes range on down to a few kilometers. Assuming that the ratio of reflecting power to size is the same for small asteroids as for large ones, we have

Absolute magnitude.....	5.0	10.0	15.0	20.0
Diameter (km).....	270	27	2.7	0.27

Since the number of bodies increases by a factor of 2.7 with each magnitude, there are probably 100,000 asteroids with diameters in excess of 250 meters. It is estimated that all the asteroids together would make up a spherical body about 1000 km in diameter with a mass less than one-thousandth the earth's mass.

Interplanetary space also contains molecular, atomic, and subatomic particles and radiation of various kinds.

In the exospheric region of the terrestrial atmosphere great numbers of nitrogen, oxygen, and other particles are freely orbiting as a highly tenuous atmosphere. At higher levels of the exosphere lighter gases such as hydrogen and helium may eventually assume an increasingly important contribution to the density and composition. The proportion of ionized particles to neutral atoms will increase to values such as one in five, and more, at greater

distances from the earth, because there will be few collisions between the very highly ionized positive ions and negative electrons; the probability for neutralization of the electric charges by recombination will be very small. At very high levels or beyond the atmosphere protons and electrons will dominate, together with some neutral hydrogen atoms. The electrons will dominate, together with some neutral hydrogen atoms. The electron density at the base of the exosphere can be taken as $3 \times 10^7/\text{cm}^3$. Indirect data on the solar corona and zodiacal light suggest that the region between the earth and moon has an electron density of the order of $10^3/\text{cm}^3$.

The lunar gaseous atmosphere may consist mainly of argon, together with carbon dioxide and sulphur dioxide and some water vapor, but its true composition and density are as yet uncertain. It is also possible that the moon has an ionosphere with electron densities of the order of $10^5/\text{cm}^3$; some estimates go as high as $10^{10}/\text{cm}^3$.

According to the Chapman-Ferraro theory of magnetic storms, corpuscular streams of electrons and protons are emitted from active regions on the sun, and proceed earthwards to cause magnetic storms and auroras. These particles, according to this theory and several others related to it, travel to the earth in about a day, so that the velocity may be about 10^8 cm/sec.

Solar particles moving with a velocity of about 1/3 that of light have been noted to leave the sun in areas of solar flares. (Methods of radio astronomy have been used in these studies.) During solar flares on about six occasions since the early 1940's, marked increases in cosmic rays have occurred over a period of hours to almost a day. On February 23, 1956, an increase of 90 per cent or so in cosmic rays detected at the ground appeared in high latitudes of the earth. This means that the particles had an energy

in excess of 18 billion electron volts (bev). Effects persisted over a period of 16 hours or more in cosmic rays, and for several days high absorption of radio waves ensued. The potential extreme radiation hazard like that of February 23, 1956, apparently does not occur very often; this and some other large increases during flares have appeared only about once every three years.

A weak galactic background of radio noise from a few to thousands of megacycles exists. It is believed to arise from electrons spiraling in magnetic fields of active areas in distant galaxies. Some localized areas radiate very intensely, as in the region of the Crab nebula.

The sun also emits a radio noise background. Since a black body at some thousands of degrees generates electromagnetic waves whose intensity varies with wavelength, there must be emission at radio frequencies as well as in the ultra-violet, the visible spectrum, and the infrared. Also, during solar flares the sun emits short bursts of radiation up to 1000 times as great as its steady background radiation.

The earth's magnetic field in space is much like that of a short magnet at the earth's center, the magnet being so directed that its north pole will lie in the general direction of the geographic poles. The central axis of this magnet intersects the earth's surface at the point 78.6° north latitude and 289.9° east longitude, called the geomagnetic north pole. The magnetic moment of this magnet, taken as a very short magnet, or dipole, was 8.06×10^{25} centimeter-gram-second units in 1922.

At points beyond the atmosphere at distance r from the earth's center, the magnetic field falls off rather nearly as the cube of the distance. The electric currents flowing in the atmosphere, believed mostly transients, add to the main magnetic field. The main field includes also some higher-

order terms required in precise calculations of the field in space.

The surface magnetic field of the sun is not much larger than that of the earth, except within sunspots. The field may vary somewhat with time, and a magnetic moment of the sun is difficult to assign. In the case of sunspots, there are usually local north and south magnetic poles in the sunspot groups. Magnetic moments may be as great as or greater than values 10^6 times that of the whole earth when spot diameters reach 50,000 - 60,000 km, with magnetic fields of the order of 5000 oersteds.

Such sunspot fields could therefore extend well beyond Mercury and almost to the planet Venus with fairly readily measurable intensity, if it were not for the fact that the solar corona is a very good electrical conductor; as a consequence, electromagnetic induction tends to nullify systematic features of the changing sunspot fields, except at points close to the sun. However, it is expected that portions of the actual magnetic fields of sunspots are carried by material within moving prominences or the streaming corona to the neighborhood of the moon and earth with measurable intensity of magnetic field. Hence, the sunspot fields are expected to exist in fragmentary and badly organized form within the solar system.

The relative heating effect of the hot solar corona on space vehicles will be negligible for a lunar flight. The heat flux from the solar corona per square centimeter of area will be kinetic energy of motion; but the hot particles, though very energetic, would be too few in number to heat up a metal surface appreciably. The number of protons and hydrogen atoms should be of the order of 10^3 to $10^4/\text{cm}^3$, so that the energy flux would be only 10^{-7} times the maximum solar radiation flux of nearly two horsepower per square meter.

EXPERIMENTATION IN SPACE

The use of space "light" for scientific experimentation will greatly add to the stock of scientific knowledge, and of course such experimentation is also necessary for the successful fulfillment of many space-flight missions. Looking beyond the IGY program, we are able to foresee such useful experiments as, for example, the refinement of basic constants (planetary masses, gravitational constant, dimensions of the solar system). For these purposes artificial asteroids (satellites of the sun) and planetary satellites, perhaps with transponding equipment for accurate range and range-rate measurement, are one possibility.

There are several other uses for artificial asteroids. When tracking techniques at the distance of Venus, for example, have been perfected, an asteroid on an orbit making a close encounter can be used with perturbation theory as a test particle for refining the mass of the planet. Asteroids carrying suitable instruments can study the effects of solar particle radiation in regions of space remote from the perturbing effects of the earth's magnetic field. If instrument-bearing asteroids could be placed in the earth's equilateral-triangle libration points, observations of the directional properties of solar flares and spots could be made. Asteroids with suitable impact counters could map the distribution of meteor streams in all parts of space to determine optimum courses for later interplanetary vehicles.

Another sort of interplanetary vehicle would be an artificial satellite of another planet. It should be possible to learn a good deal about planets and their atmospheres from satellite observing stations. A logical prelude to actually landing on a planet (though probably not a necessity for Mars or Venus) would be observation of the behavior of an instrumented

're-entry body' as it plunged into the planet's atmosphere. From a knowledge of its approach trajectory and a time history of altitude, deceleration, and vehicle surface heating, the atmospheric data necessary to design subsequent entry vehicles could probably be determined.

What is the present state of knowledge concerning these neighbors of the earth?

First, Venus. Actually very little is known about Venus. Its rotation period is very uncertain; since it has no satellites, its mass is known to only 3 per cent; and since it is covered with opaque clouds, nothing concerning its surface is known. Even the chemical composition of the Venusian atmosphere is controversial. Large amounts of carbon dioxide have been observed but no evidence of water or oxygen. Some believe that Venus is a dry, dusty planet covered with an opaque dust cloud. Others believe that Venus is one vast ocean, and that water has not been detected in the atmosphere because it is always in the form of ice. Still others believe that the clouds are formaldehyde and that Venus is covered with plastics. These hypotheses are not idle speculations but are consistent with the observations. It is the difficulty of getting suitable observations that leaves the conditions on Venus so uncertain.

Barometric observations of Venus suggest some rotation. Richardson has recently concluded that Venus has a rotation period of from 8 to 46 days, with a probability of being correct of 0.5. He claims that 14 days retrograde is the best mean value. The axis, as ascertained from cloud markings, is tilted from the plane of the orbit somewhere between 14 and 52 degrees (not so different in this respect from the earth and Mars). The facts that no equatorial bulge has ever been observed and that radio measurements showing

a 13-day fluctuation have been observed strengthen the case for Richardson's 2-week Venusian day. That oxygen has or has been observed may be traced to the fact that all observations are restricted to the upper parts of the atmosphere, where oxygen is probably dissociated as in the earth's atmosphere.

All of these statements add up to the probability that Venus will be a 'surprise planet' when visited by pioneer astronauts. Nothing is definitively known which precludes the existence of conditions favorable to life. And at least one prominent astronomer feels that Venus will be the planet on which we are most likely to find life.

As to the earth's other neighbor, Mars, a great deal more is known. Mars rotates on its axis in $24^h 37^m$ or essentially one earth day. Its axis is inclined to the orbital plane by the same amount as the earth's, and seasonal effects similar to those of the earth are observed.

The conditions on the surface of Mars are very similar with regard to temperature and pressure to conditions on the earth 11 miles above the surface in the stratosphere. Although human life could not survive without extensive local environmental modifications, the possibility of a self-sustaining colony is not ruled out.

But bleak and desert-like as Mars appears to be, with no oxygen and very little, if any, water, there is good evidence (derived from observation of the Martian dark areas and seasonal color changes) that some indigenous life forms may exist.

The usual controversy is still unsettled and probably will remain so until Mars can be adequately observed from a position free from the blurring motions of the earth's atmosphere.

Already, through the study of cloud movements and temperature distributions on Mars, knowledge is being gained which is useful in the analysis of the earth's atmosphere.

Each planet, regarded as a scientific laboratory, offers unlimited possibilities for studying physics, geology, meteorology, chemistry, and even life sciences. The scientific dividends from the exploration of space should, in not too long a period, repay the whole cost many times over.

It has been noted that nearly all the physical attributes of the exosphere, solar corona, and lunar atmosphere are so ill-known that it is highly desirable to conduct the basic research needed to remove the dearth of real knowledge.

Among the physical experiments that might be conducted (in addition to those mentioned above) are the following:

- a Measurements of the composition, density, and temperature of matter along the path of a lunar flight, and on the moon.
- b Measurement of x-ray and ultra-violet radiation along the flight path. Some attention to infrared radiation also seems indicated.
- c Measurement of the spectrum and intensity of radiation at radio frequencies (a) from space, (b) from the sun, and (c) from sunspots.
- d Measurement of the geomagnetic field at various distances and of possible magnetic fields accompanying auroral streamers and ring currents. Turbulent magnetic fields within the solar corona should also be measured. The lunar magnetic field should be ascertained, right down to the lunar surface.

- o Cosmic ray observations with counters along the flight path. On the moon, directional experiments will be useful in the study of cosmic radiation from the sun or special sources requiring precise location.
- o Precise measurements of the lunar mass and gravitational field.
- o A mass spectrograph on the moon to identify gases such as argon, neon, krypton, carbon dioxide, sulphur dioxide, and water vapor.
- o Seismic observations, with or without explosions, to provide information on the lunar interior and composition.
- o Measurement of radioactivity at various depths within the moon.

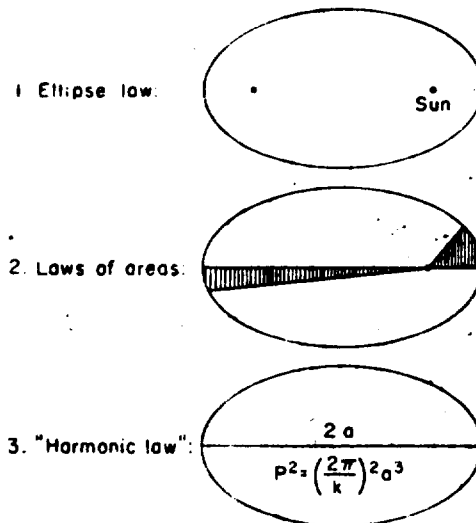


Fig. 1 — Kepler's laws

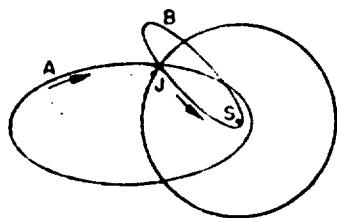


Fig. 2 — Perturbations

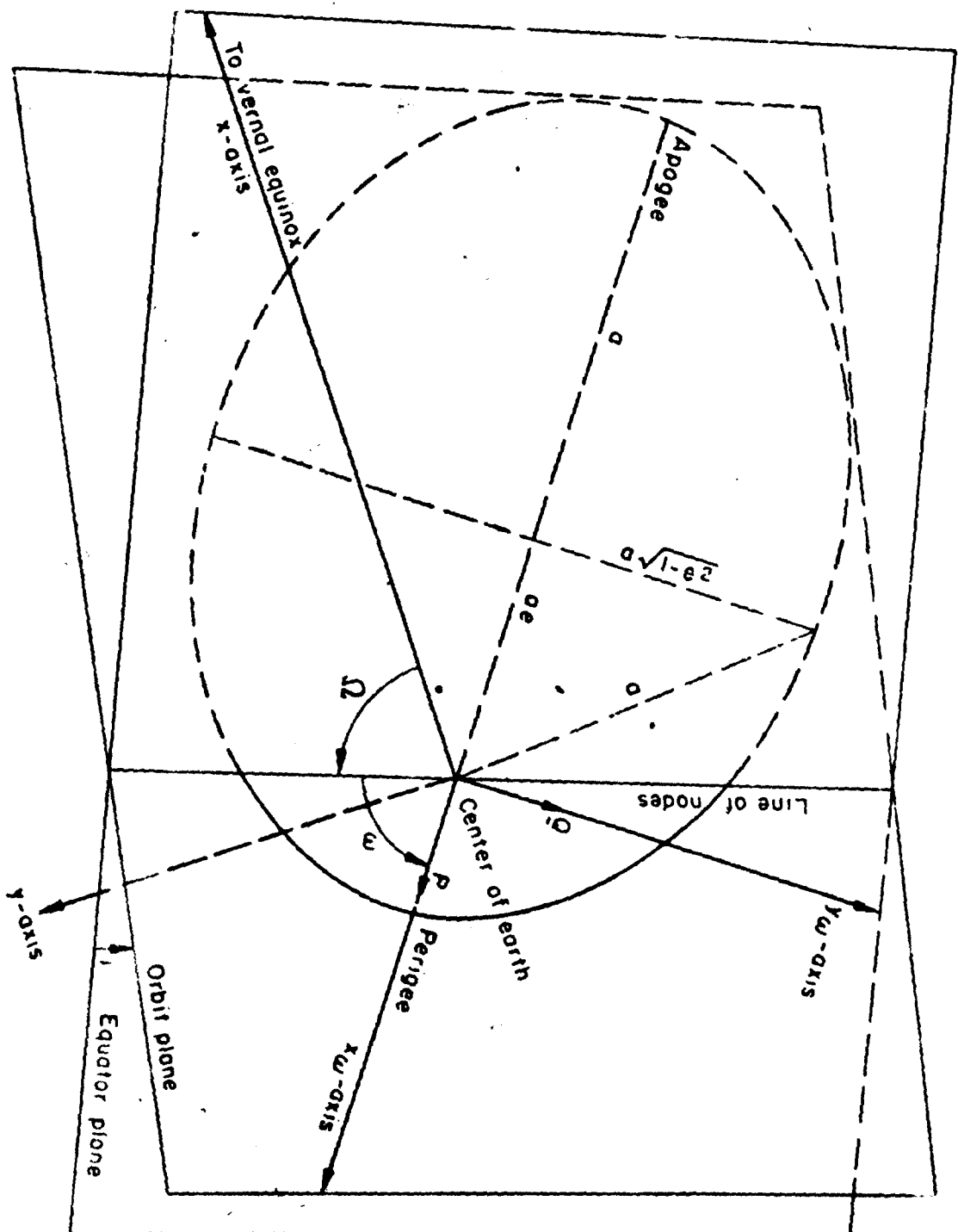


Fig. 3 — The elements of an orbit

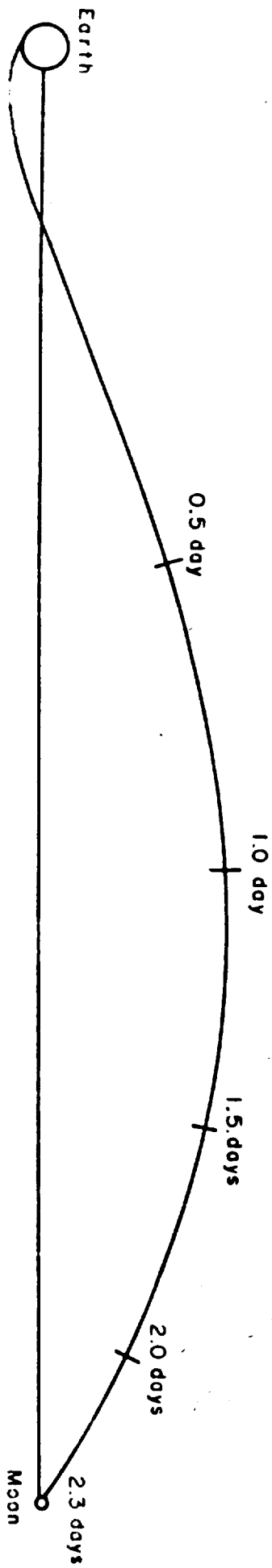


Fig. 4 — Moon-rocket trajectory in rotating space

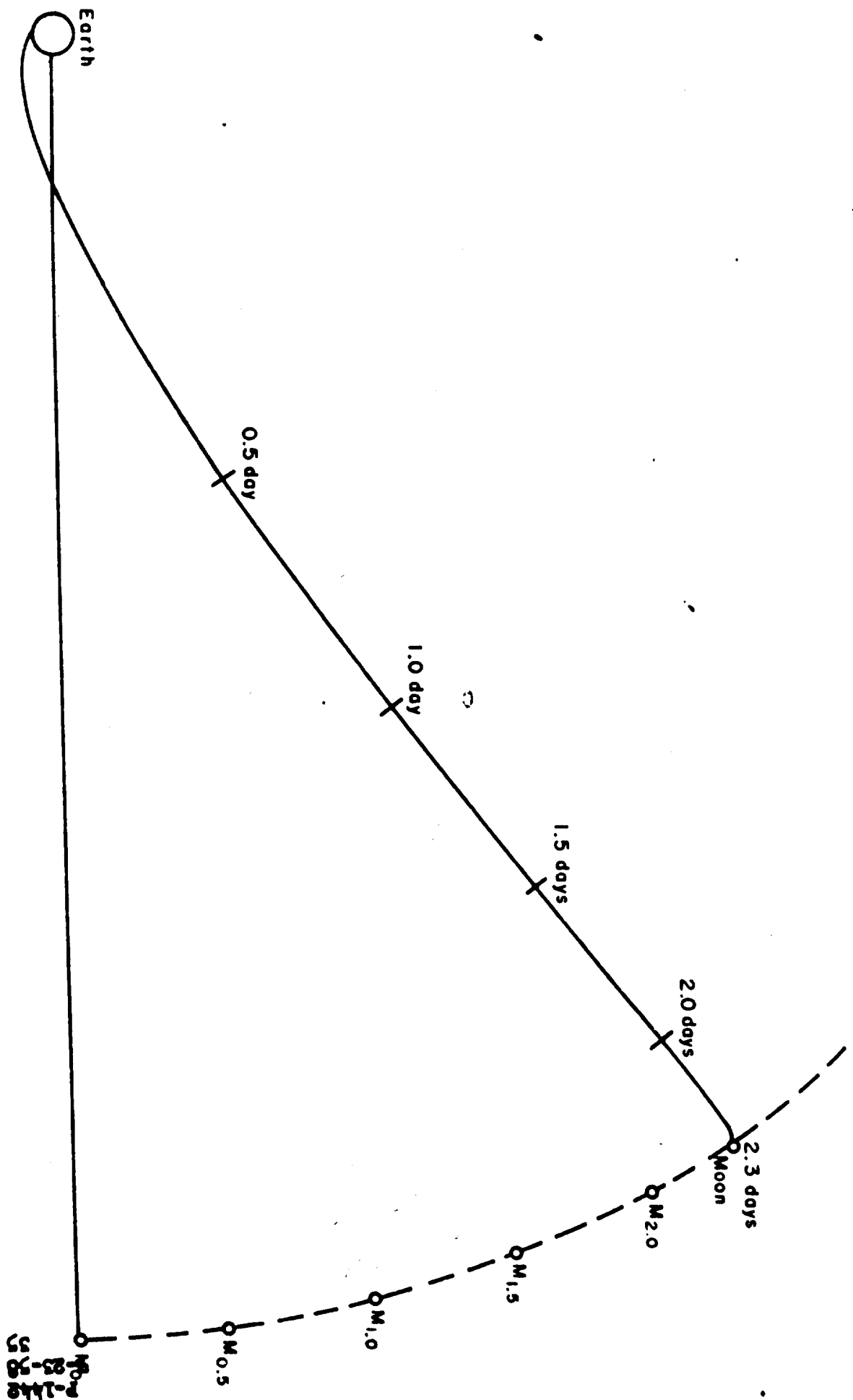


Fig. 5—Moon-rocket trajectory in inertial space

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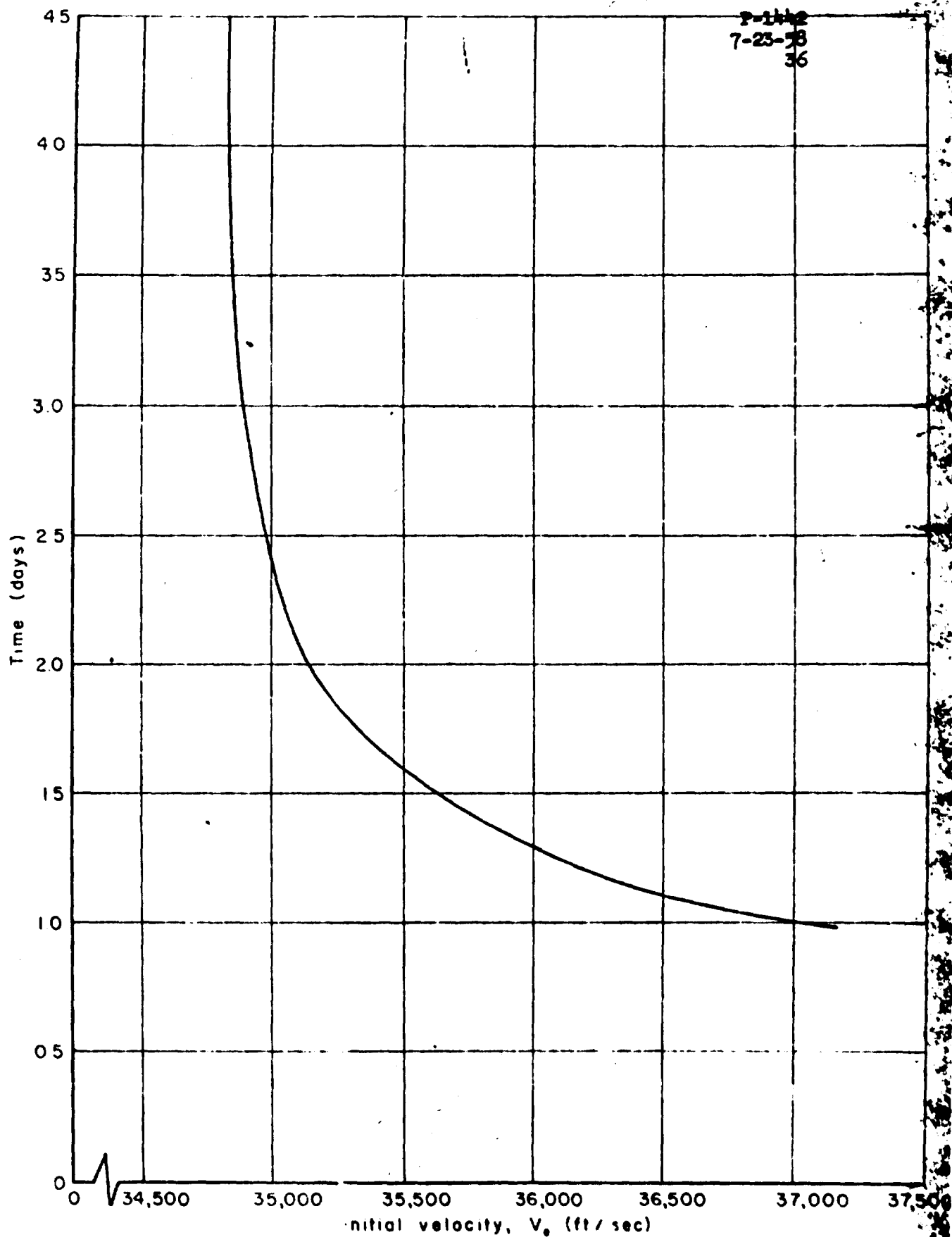


Fig. 6 — Transit time from Earth to Moon

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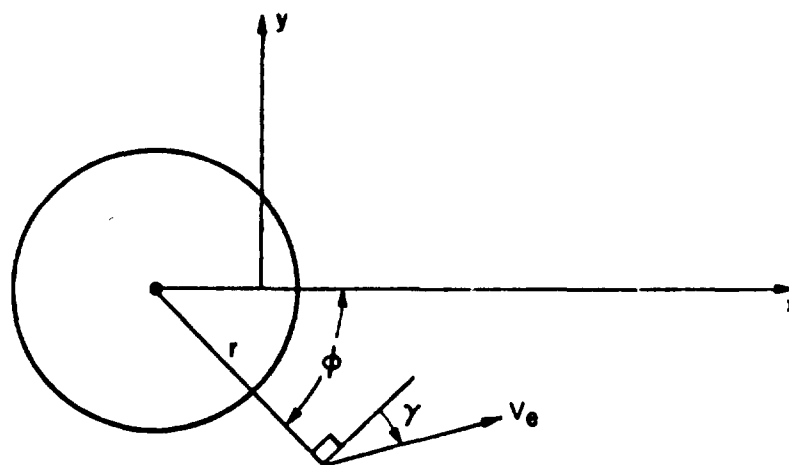


Fig. 7 — Parameters used to describe initial conditions

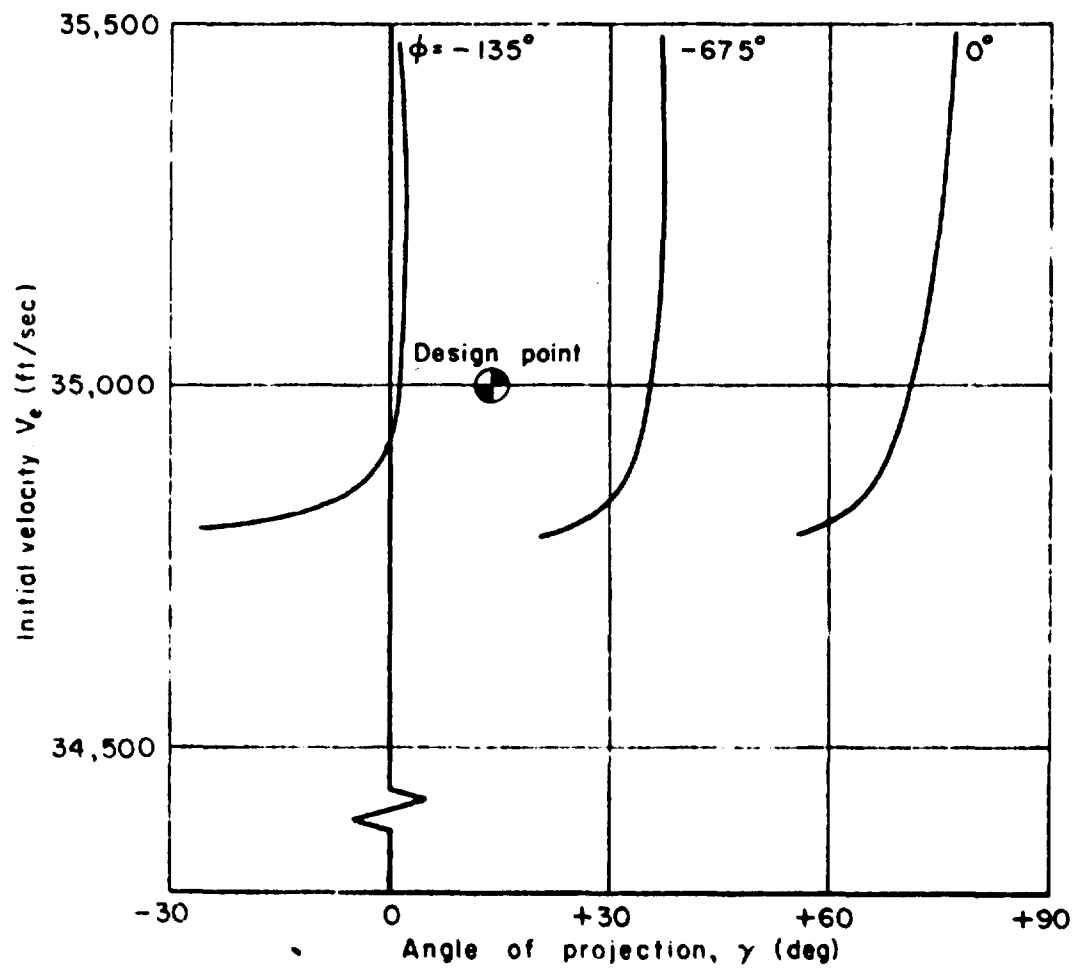


Fig. 8—Combinations of V_0 and γ required to hit the Moon from various initial positions

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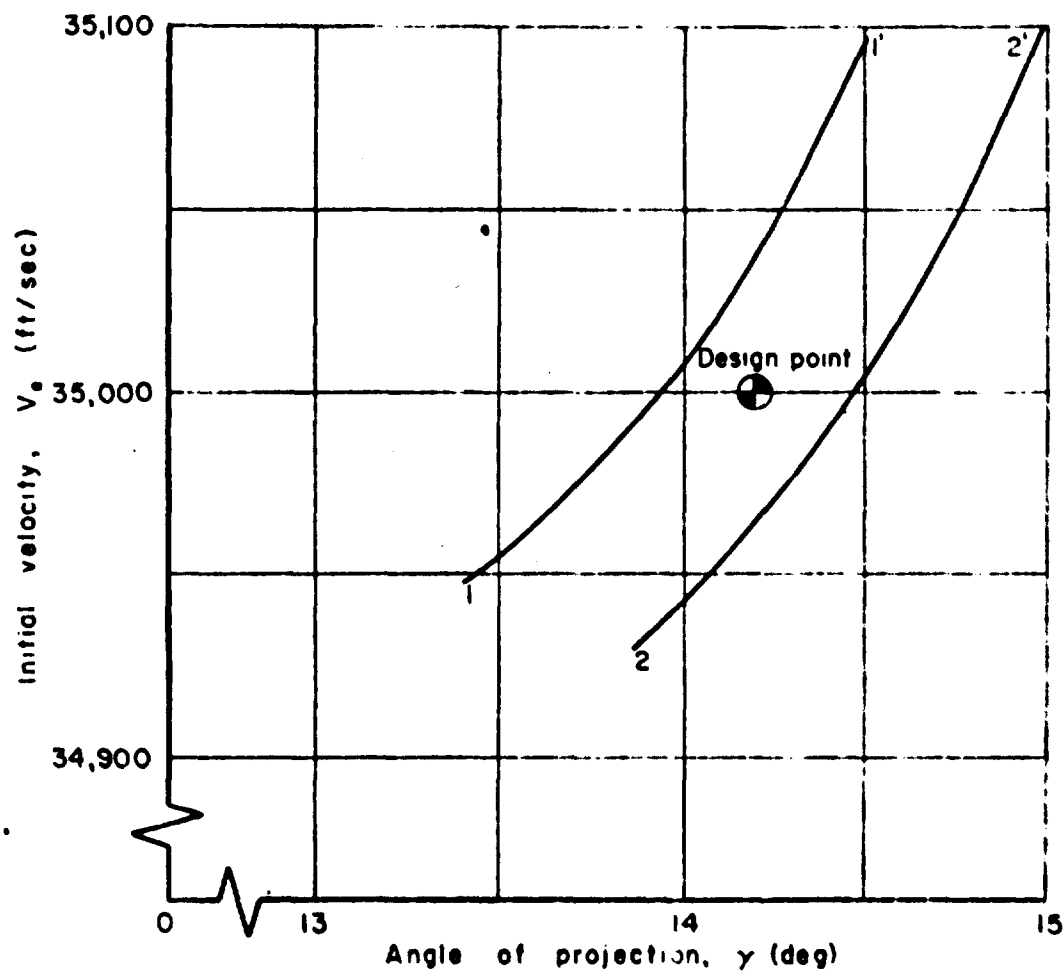


Fig. 9 — Hit-band region around design point

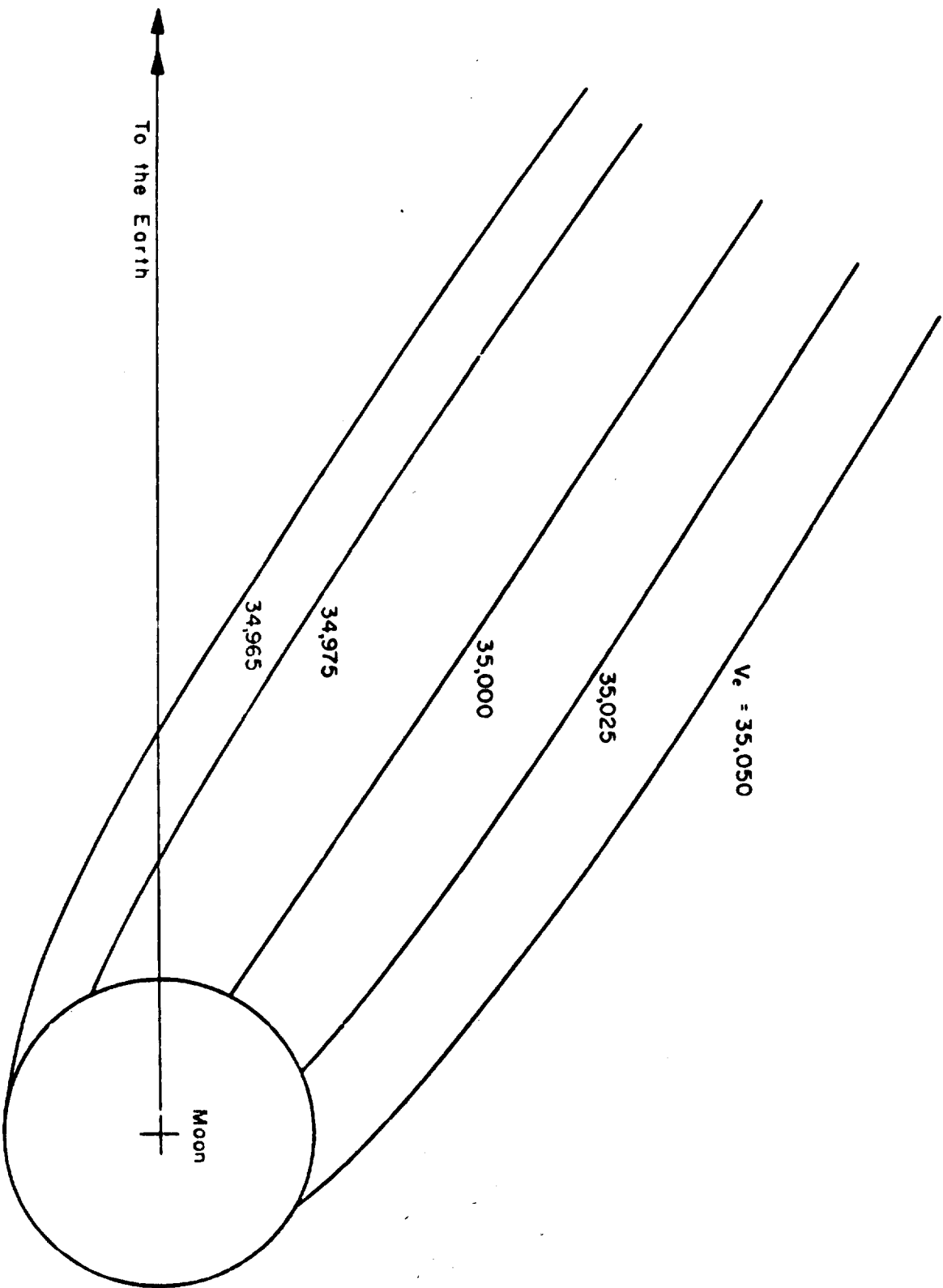
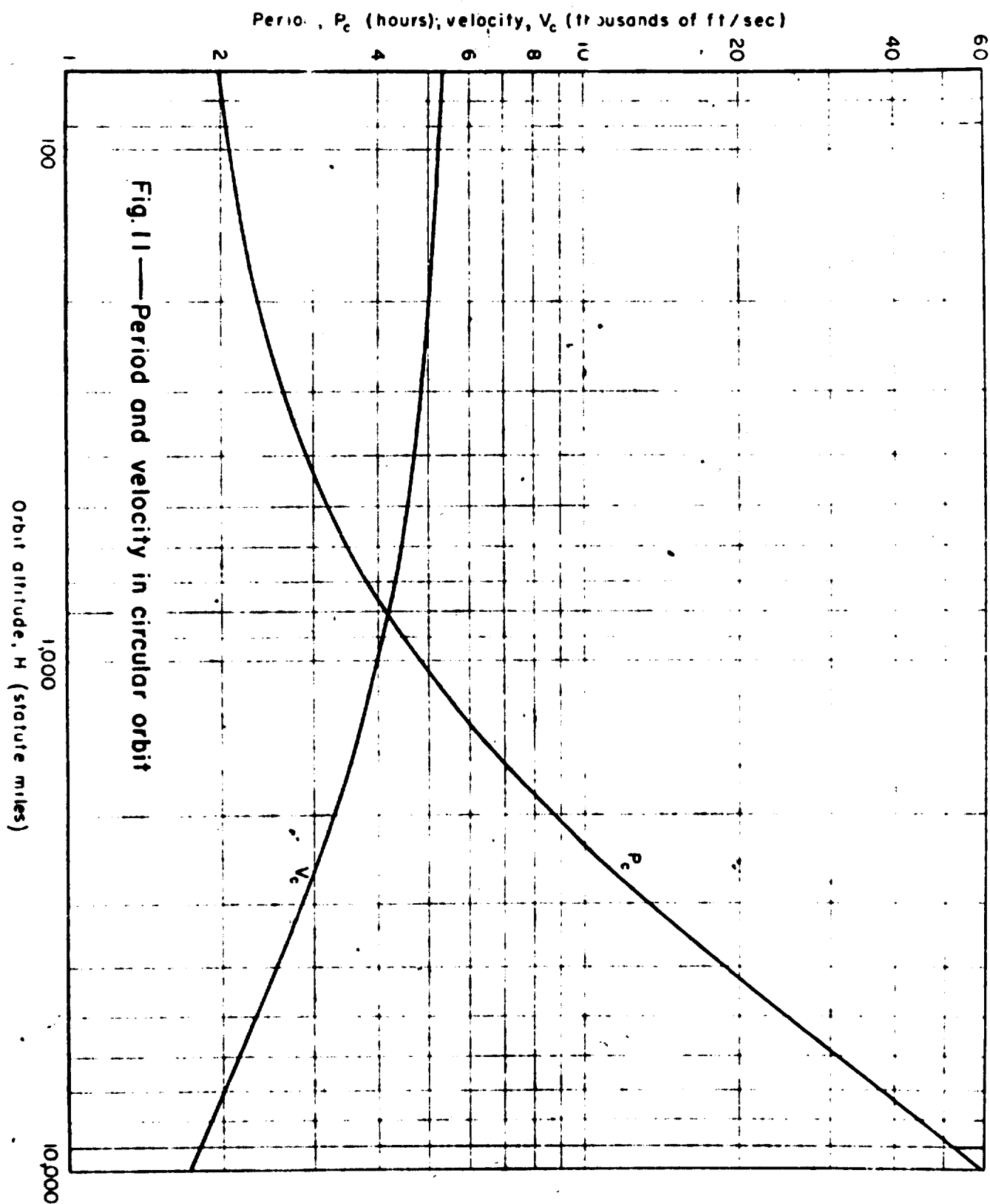


Fig. 10—Effect of varying V_e on hit point

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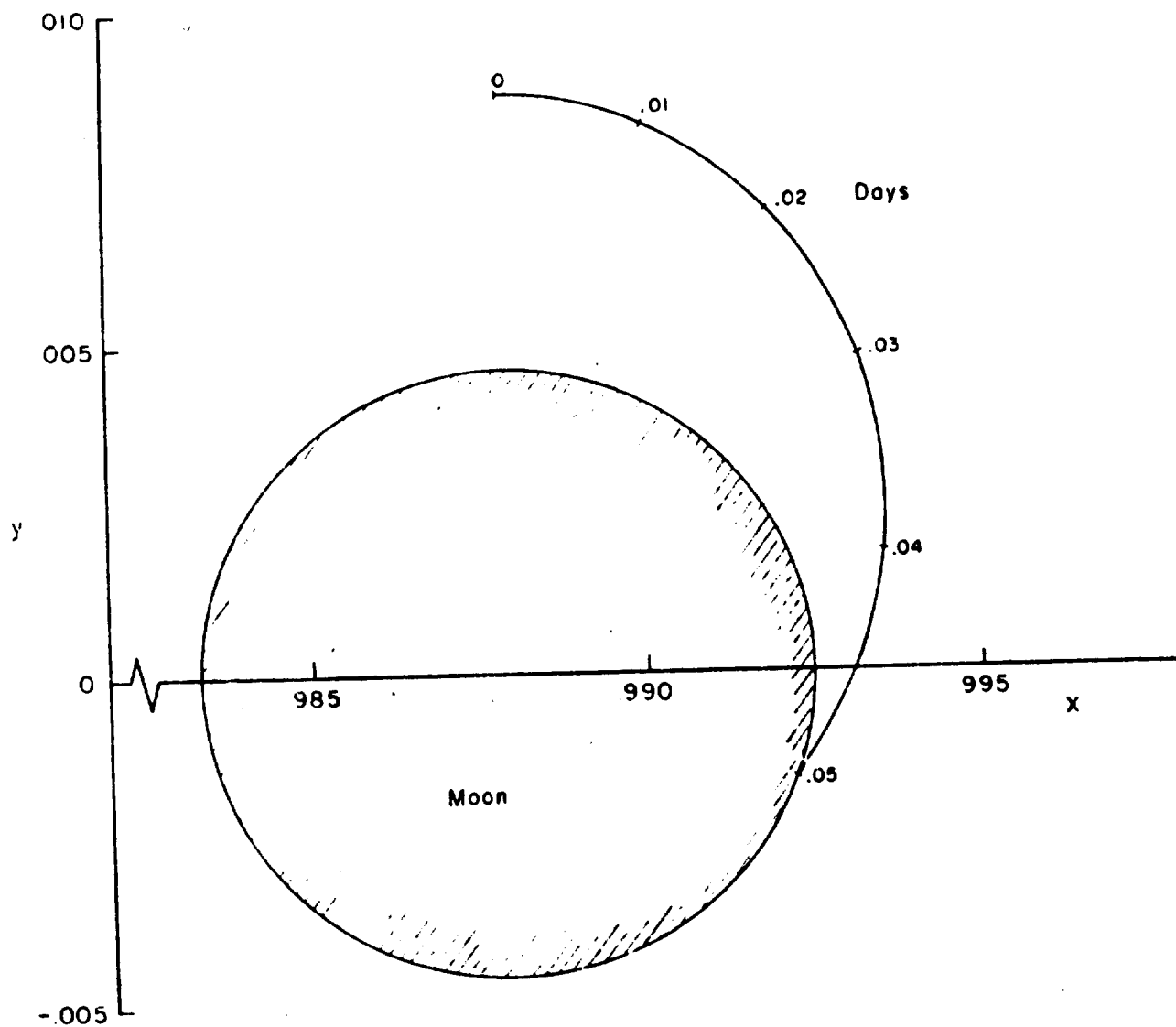


Fig. 12 — Collision due to insufficient initial velocity

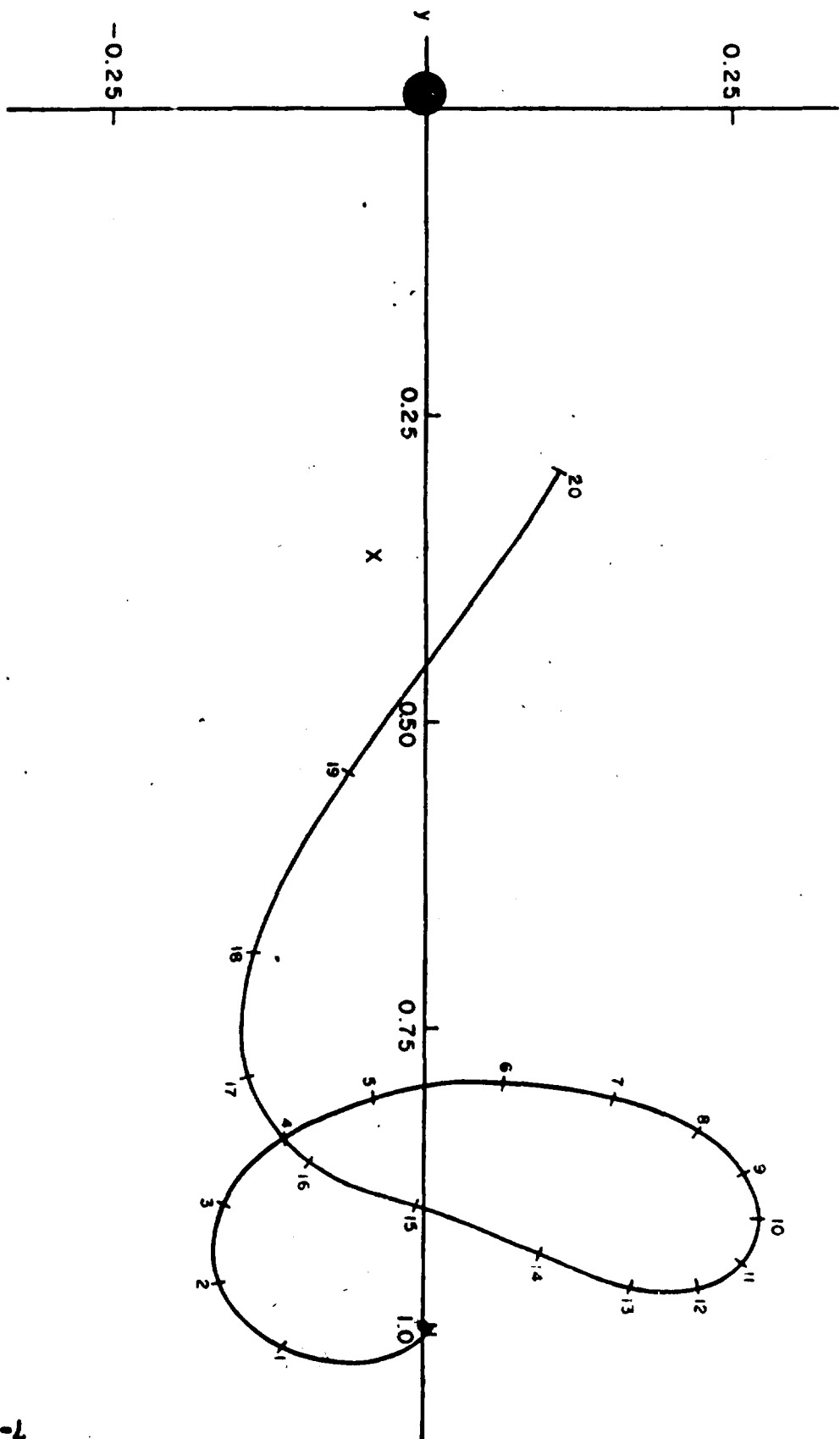


Fig. 13 — Recapture of lunar satellite by the earth

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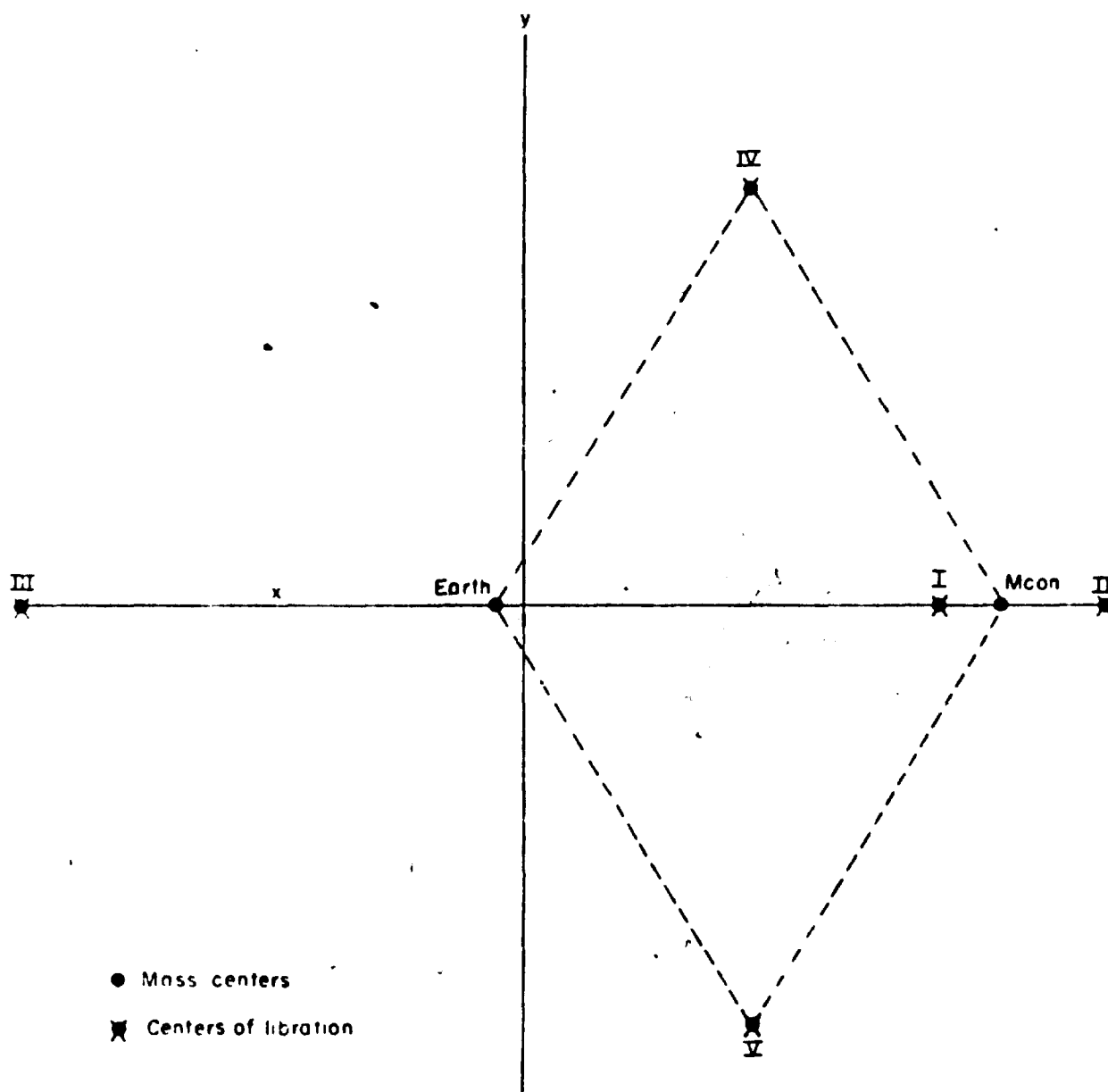


Fig. 14 — Relative positions of libration centers

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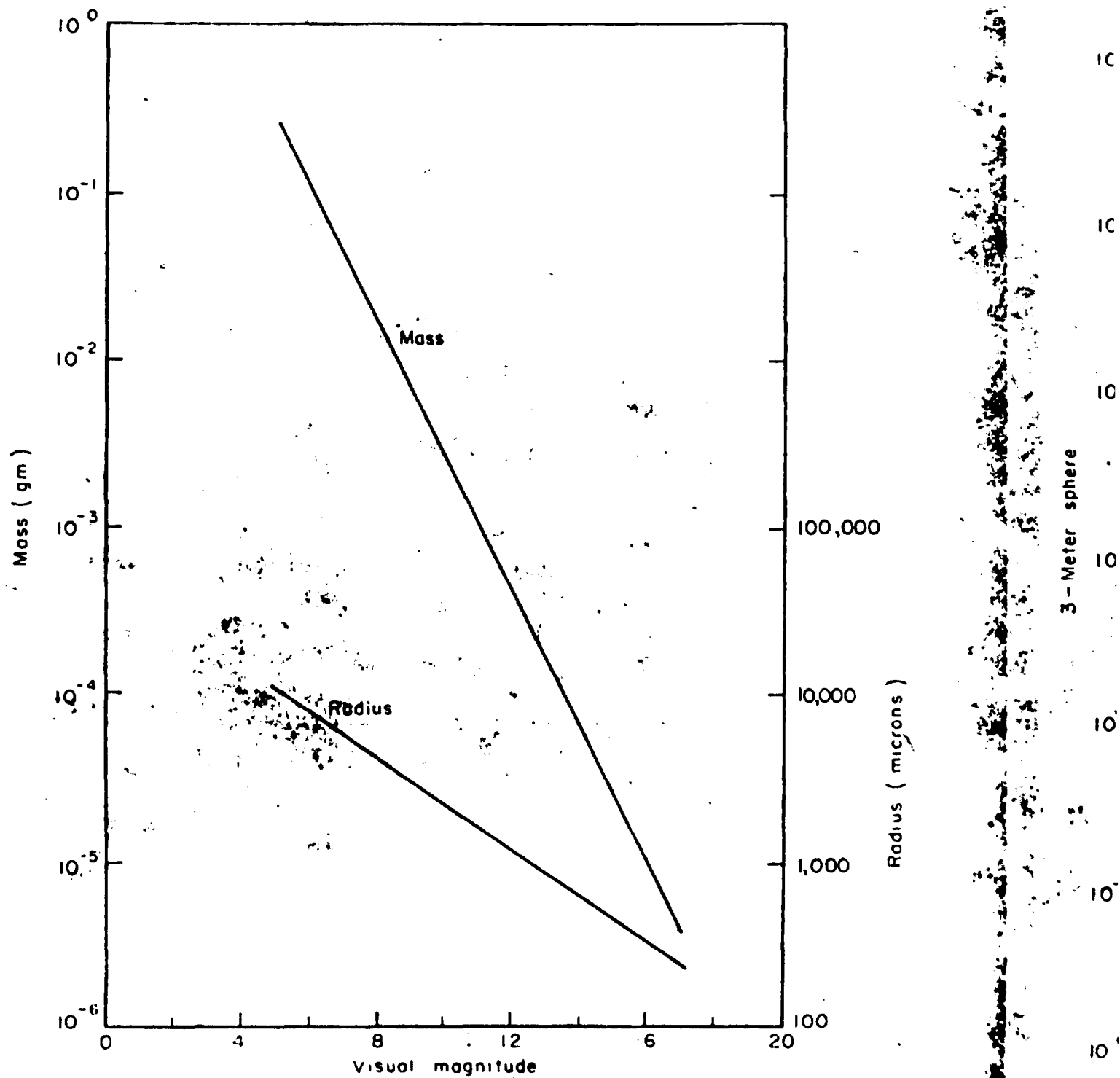


Fig. 15 — Meteor brightness vs size

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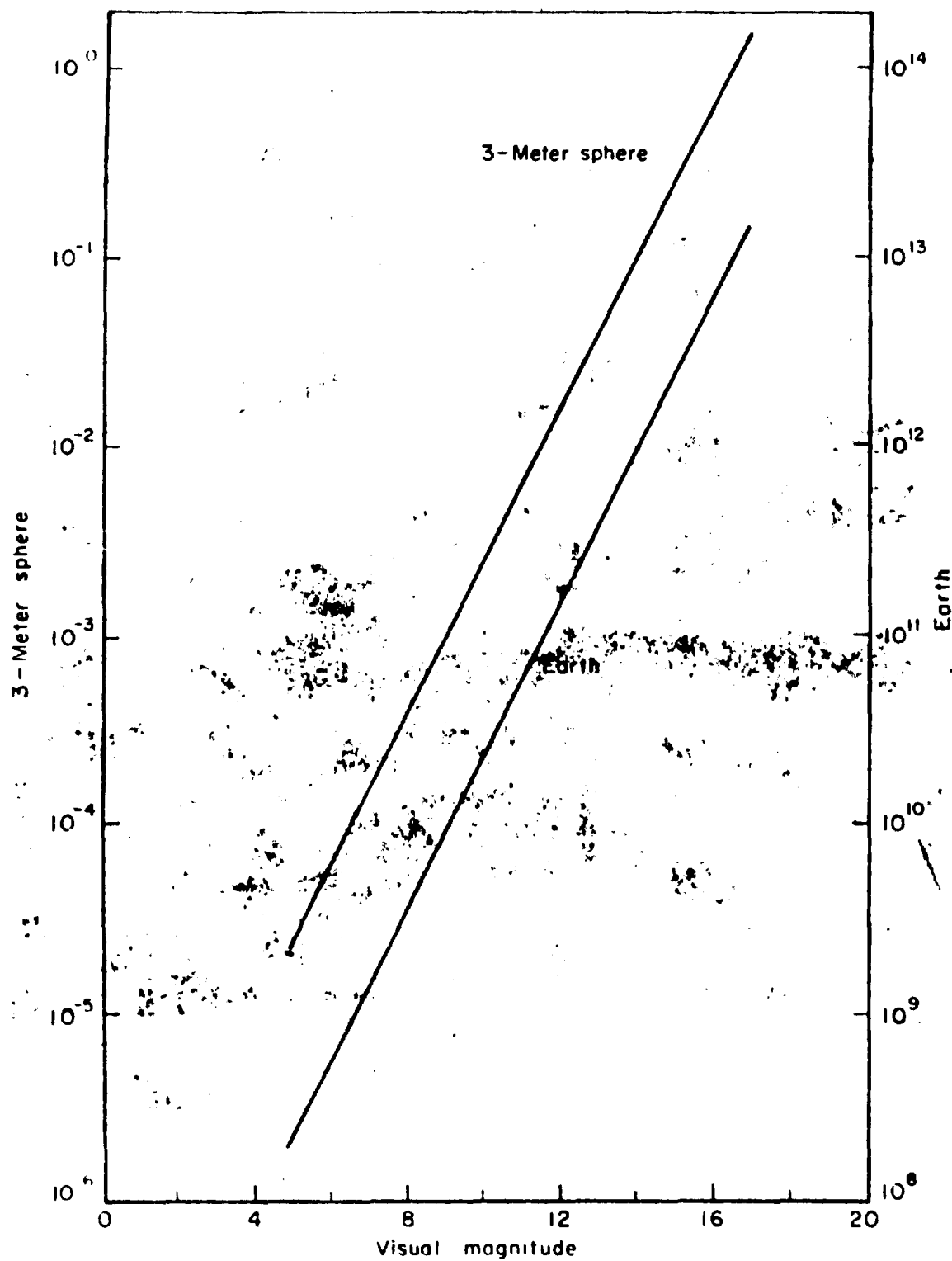


Fig. 16 — Meteor impacts per day

FIG. 17

CHANGE OF BRIGHTNESS OF THE SUN'S OUTER CORONA
AND THE ZODIACAL LIGHT WITH DISTANCE
FROM THE SUN

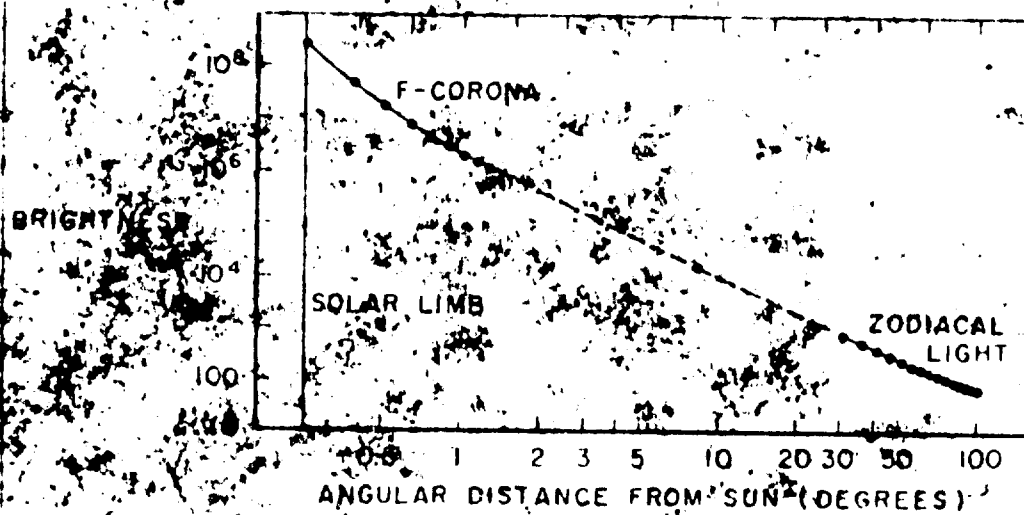


FIG 18

THE TROJAN ASTEROIDS

TROJANS

A diagram of the Trojan asteroids. It features a large, irregularly shaped central mass, possibly representing Jupiter, with a smaller, more circular mass labeled 'TROJANS' positioned to its right. The entire diagram is enclosed within a rectangular border.